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POWER TRANSISTOR COOLING IN A SPACE ENVIRONMENT

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SUMMARY

The cooling of power transistors was investigated in a space environment, where the only available mode of heat transfer is conduction to a heat sink and radiation from the heat sink to space. An attempt was made to minimize the thermal resistance between the transistor case and the heat sink, so that the transistor would dissipate as much power as possible while maintaining its temperature within the maximum tolerable level to prevent thermal runaway. Further, it was necessary to electrically insulate the transistor from the heat sink. Beryllium oxide washers provided electrical insulation and added very little to the thermal resistance between case and sink, the BeO being a good heat conductor. However the problem of contact thermal resistance at each interface arose, especially in vacuum; this contact resistance provided practically all the thermal resistance between case and sink. The effect on the contact resistance of surface pressure, insertion of foil, and soldering was examined. It was concluded that, for the most efficient cooling, indium foil should be inserted at each interface, the indium foil having the effect of reducing the contact resistance in vacuum by a factor of 8.

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INTRODUCTION

The problem of maintaining the junction temperature of a transistor within certain limits to prevent runaway and failure is well known. The work performed to date has been concerned with transistor cooling in an atmospheric environment, by either free or forced convection. Typical of the work in this area is that performed by Abel (Reference 1) and others (Reference 2). The investigation performed here, however, had the purpose of extending present knowledge to cover transistor cooling in a space environment.

The only mode of heat transfer available in space is radiation, either directly from the transistor or from a heat sink to which the transistor is thermally coupled. Calculations show that the surface area of the transistor is too small to provide more than a few milliwatts of direct radiative heat dissipation, whereas several watts may have to be dissipated. Therefore the problem resolves itself into an investigation of the thermal path between the transistor junction and the heat sink, with the goal of making the thermal conductance as high as possible.

Figures 1 and 2 show how a typical power transistor is mounted on a heat sink. Two thermal paths are available: one from the case, through the top washer, to the heat sink; and the other from the case, through the stud and nut, through the bottom washer, to the heat sink. Essentially, the thermal resistances are in parallel.

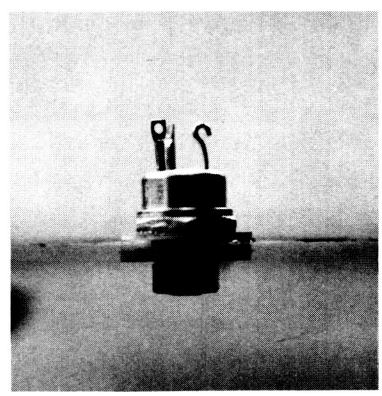

Figure 1—Mounting of 2N1724 transistor on anodized aluminum heat sink, using two BeO washers.

The net thermal resistance desirably should be as low as possible. However it is often necessary that the transistor be *electrically* insulated from the sink. This means that some sort of device, such as a washer, must be used to provide good thermal conductivity while serving as an electrical insulator. Further, if washers are to be used, they must have good mechanical properties to resist cracking when the nut on the transistor is tightened during mounting. Materials satisfying these specifications, to a greater or lesser degree, are beryllium oxide (Reference 3), mica, and aluminum oxide.

*Work was performed by the authors for the NASA Goddard Space Flight Center Summer Workshop Program 1962.

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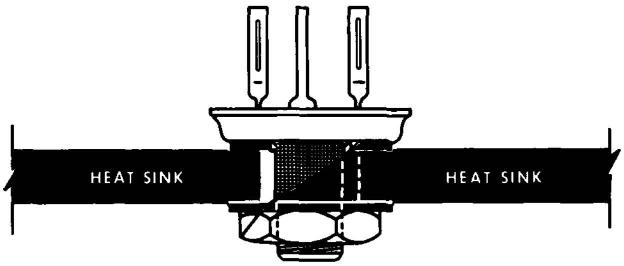

Figure 2—Mounting of a typical power transistor.

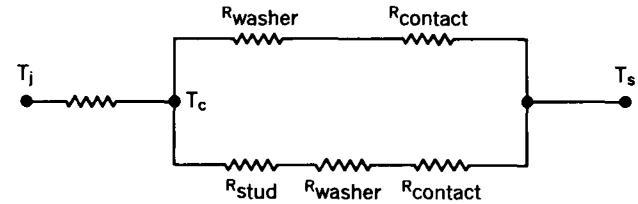

Figure 3—Thermal network.

Figure 3 shows the thermal network. All quantities are readily determinable with the exception of contact resistance (the thermal resistance at the interface of two different materials).

Contact resistance is due to improper thermal contact between the two materials. Since no surfaces are perfectly smooth, they touch only at a limited number of points—the remainder of the space being filled with a nonconducting vacuum. Variables affecting the contact resistance include the pressure between the two surfaces, the smoothness of the surfaces, the materials themselves, and the possible addition of greases, solders, or some soft material to fill the empty regions between the surfaces.

Several theoretical and experimental investigations have been made in the general area of thermal contact resistance. Theoretical considerations must necessarily assume an idealized shape of contact point and a distribution of contact points. An analysis carried out by Fenech and Rohsenow (Reference 4) attempted to predict, with some degree of success, the thermal conductance of metallic surfaces in contact. It is felt, however, that an analysis of this type can be at the best only a fair approximation and that experimental values should be determined. Several investigators have done experimental work (References 5, 6, and 7); their results are not considered applicable to this problem because the data were obtained in air, not in vacuum. Also, their data necessarily depended on the configurations of the surfaces they employed, which were somewhat different from the ones dealt with herein.

Tests were run to determine the thermal resistance from transistor case to heat sink as a function of the previously mentioned variables. It was hoped to minimize this thermal resistance so as to provide a practical means of cooling in a space environment.

EXPERIMENTAL APPARATUS AND PROCEDURE

In this experiment the junction temperature, case temperature, heat sink temperature, and energy dissipated per unit time were measured for each test. Variations in contact resistance were introduced by applying different torques on the transistor nut with a torque wrench and by employing various interface materials such as foils and solders. Variation in surface smoothness was not undertaken because of the difficulty of measuring and controlling this parameter; in any case, it was felt that this could offer only limited improvement.

Case and heat sink temperatures were measured with copper-constantan thermocouples and a potentiometer. The thermocouples were fastened to the surfaces with aluminum tape, as shown in Figure 4. Two thermocouples were used on the heat sink, one at the base of the transistor, and the other at the extreme edge of the heat sink; and a third thermocouple was used on the case.

Because the collector junction was inaccessible to a thermocouple, its temperature had to be measured indirectly. Junction temperature T_j was determined by measuring the forward voltage drop V_{CBO} from collector to base with emitter open, since this voltage is directly dependent on junction temperature. Appendix A explains the technique employed and gives a schematic of the circuit used to make this measurement.

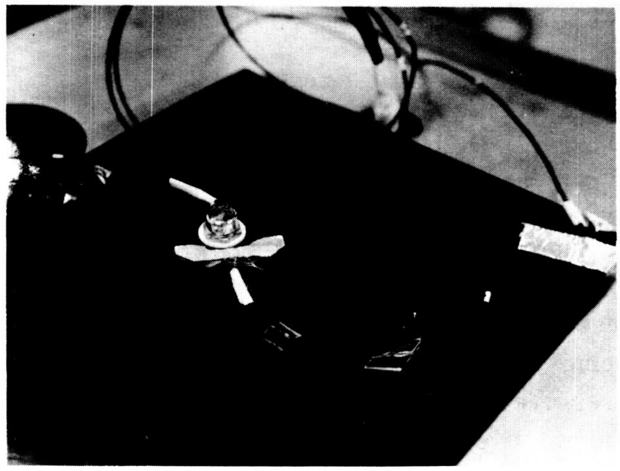

Figure 4—Location of thermocouples on anodized aluminum heat sink.

Figure 1 shows a typical power transistor (2N1724, used for all tests) mounted on a $10 \times 10 \times 1/16$-inch black anodized aluminum plate, which served as a heat sink. In this configuration, beryllium oxide (BeO) washers were placed between the transistor case and the aluminum plate, and between the nut and the bottom of the plate. The transistor stud was 1/4 inch in diameter, and the hole through the plate was 5/16 inch. The transistor base diameter was 3/4 inch. All the BeO washers were 1/16 inch thick.

An environmental pressure of approximately 2×10^{-5} mm Hg was obtained with a bell-jar vacuum system employing a mechanical fore pump and an oil diffusion pump. In the tests made under both atmospheric and vacuum conditions, the measuring procedure was the same. Power was applied to the transistor from a constant-voltage power supply, and all temperatures were allowed to stabilize for approximately 30 minutes. The junction, case, and heat sink temperatures were then measured; and the temperature difference between the case and the sink was calculated. The thermal resistance was obtained by dividing the temperature difference by the input power. The input power was set at several different levels, and the procedure was repeated at each level.

RESULTS

Table 1 is a compilation of the experimental data obtained in this investigation, both in air and in vacuum.

Early in the program it became apparent that the thermal resistance of the BeO washer ($R = L/Ak = 0.02\,°C/watt$*) was much lower than the thermal contact resistances. Hence, instead of

*Where L is the heat path length, A is the cross-sectional area normal to the heat flow path, and k is the thermal conductivity of the material.

Table 1

Experimental Data Obtained in Air and in Vacuum.

Configuration	Vacuum or Air	Torque (in.-lb)	θ_{c-s} (°C/watt)
2 BeO washers	Vacuum Air	6 6	4.79 1.19
2 BeO washers + 3 indium foil washers	Vacuum Air	6 6	0.61 0.50
2 BeO washers + 3 aluminum foil washers	Vacuum Air	6 6	1.59 0.81
2 BeO washers + 3 copper foil washers	Vacuum Air	6 6	3.15 1.04
2 BeO metallized washers + 3 indium foil	Vacuum Air	3 3	0.71 0.54
	Vacuum Air	6 6	0.66 0.50
	Vacuum Air	9 9	0.61 0.43
	Vacuum Air	12 12	0.55 0.42
2 BeO metallized washers	Vacuum Air	6 6	4.40 1.12
2 BeO metallized washers + 2 indium foil + transistor soldered to washer (indium solder)	Vacuum Air	6 6	0.49 0.40
Transistor soldered to metallized washer (indium solder), washer soldered to plate; 1 BeO washer + indium foil on bottom	Vacuum Air	6 6	0.56 0.43
1 BeO washer + 2 indium foil; stud insulated	Vacuum Air	6 6	0.70 0.49
2 BeO washers + 2 indium foil + Apiezon grease on threads	Vacuum Air	6 6	0.57 0.47
No washers	Vacuum Air	6 6	5.16 1.36

**Washer dimensions:* O. D. - 0.90"; I. D. - 0.26".

testing the effects of different washer materials, it was decided to use BeO exclusively since little improvement over BeO could be expected.

Effect of Environment

Figure 5 illustrates the increase in thermal resistance between the transistor case and the heat sink in a vacuum as compared with the resistance in air. In a vacuum the only mode of heat flow between the surfaces is conduction through the few discrete contact points; in air there is also the possibility of heat convection between the surfaces or heat conduction across the narrow air layer. The presence of a vacuum thus tends to amplify the cooling problem.

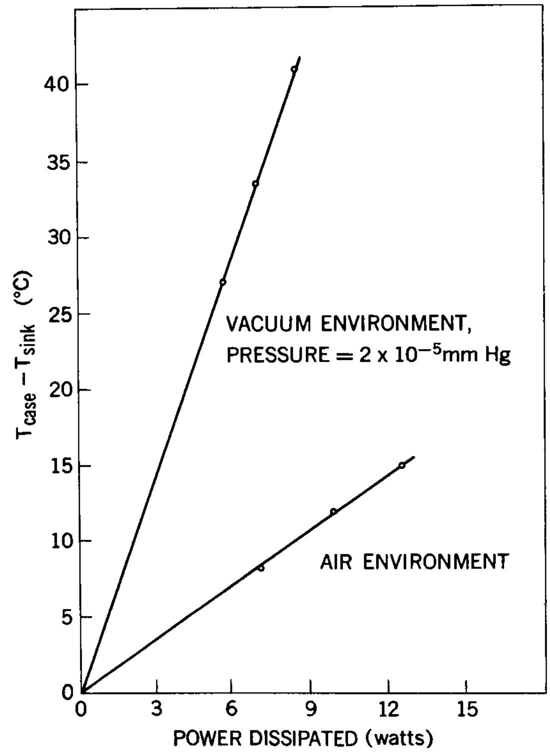

Figure 5—Effect of environment on thermal resistance. 2N1724 transistor mounted on anodized aluminum heat sink; 6 in.-lb torque on nut; 2 BeO washers, no foils.

Use of Foils

Figure 6 illustrates the effect of using foils along the interfaces of the BeO washers in a vacuum environment. In each case, a foil washer with the same surface dimensions as the BeO washer was placed between the transistor case and the top washer, between the top washer and the heat sink, and between the bottom washer and the heat sink. The graph shows that the use of any of the three interface materials lowered the thermal resistance from case to heat sink. Indium foil, however, proved most effective and lowered the thermal resistance to 0.61°C/watt, approximately 1/8 of its value without interface material.

The foil's effect is to fill the void between the surfaces with heat-conducting material. The softness of the foil seems very critical in determining its effectiveness. Indium, by far the softest of the foils, in most cases was found to adhere to the contact surfaces because of the penetration of contact points into the foil.

Surface Pressure

The effect of surface pressure on thermal resistance is shown in Figure 7. The transistor was mounted with two BeO washers and three indium washers as interface material, and the torque on the nut was varied from 3 to 12 in.-lb in 3 in.-lb steps. As the graph illustrates, thermal resistance decreases linearly with an increase in surface pressure. Greater pressures probably would result in a still smaller thermal resistance; however the cracking of the washer limited further tightening of the nut.

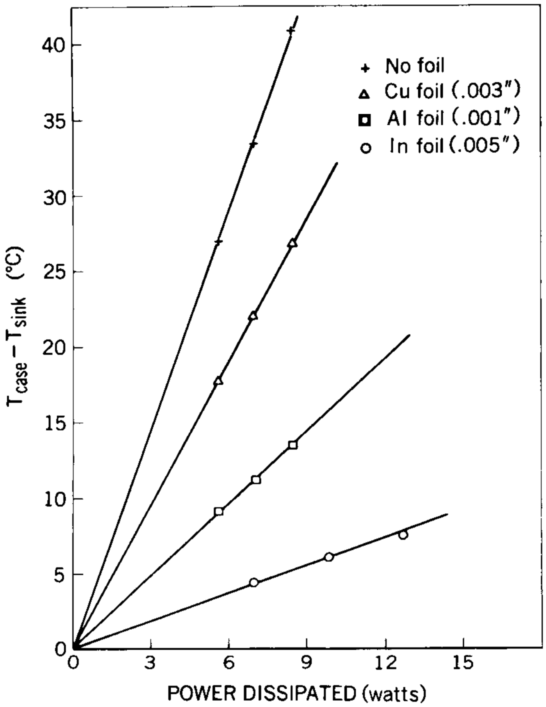

Figure 6—Effect of interface foil on thermal resistance in a vacuum environment. 2N1724 transistor mounted on anodized aluminum heat sink; 6 in.-lb torque on nut; 2 BeO washers; environmental pressure = 2×10^{-5} mm Hg.

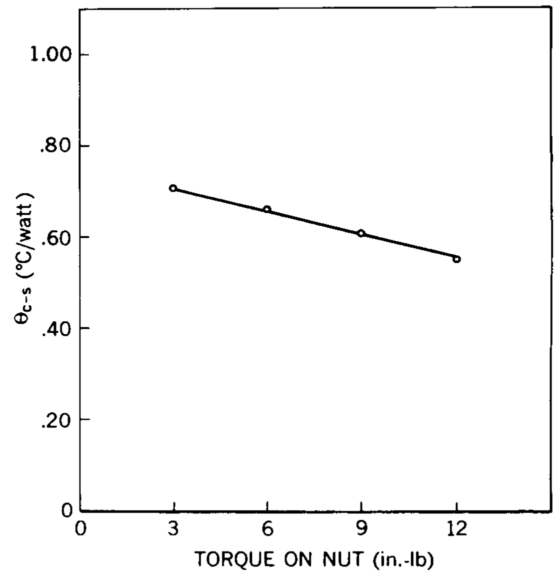

Figure 7—Effect of surface pressure on thermal contact resistance from case to sink, θ_{c-s}, in a vacuum environment. 2N1724 transistor mounted on anodized aluminum heat sink; 2 BeO washers with indium foil used at all interfaces; environmental pressure = 2×10^{-5} mm Hg.

This increase in conductivity is believed to be due to further penetration of the indium into the voids as the surfaces are further compressed.

Effect of Soldering on Contact Resistance

One way of reducing thermal contact resistance is to solder the surfaces together: in this case, soldering transistor to washer, and then washer to heat sink. As the ceramic washer material cannot be directly soldered, the beryllium oxide must be metallized and then copper- or silver-plated. The metallizing was accomplished by depositing on the washer surface a molybdenum manganese compound, a process carried out by the National Beryllia Corporation or the Brush Beryllium Company. The first tests made were for the purpose of investigating any change in thermal contact resistance due to the use of plated rather than unplated washers. With the same configurations, plated and unplated washers gave about the same value for contact resistance. Next, the plated washer was soldered to the transistor and also soldered to the aluminum heat sink, the heat sink being nickel-plated to hold the solder more easily. A low melting point, indium-alloy solder was used on the transistor to avoid any possible damage to it. Results showed that the soldering reduced the thermal resistance to roughly the same level as that achieved using indium foil in the interfaces.

To determine the magnitude of heat conduction through the stud, nut, and bottom washer in relation to that path through the top washer, the stud was insulated with Teflon and paper; and conduction was allowed only through the upper path. The change in thermal resistance was so small that the lower path might almost be neglected when a good conductive configuration such as the indium-BeO washer method is used for the upper path. The high resistance of the lower path is thought to be caused mostly by ineffective contact between the screw threads and the nut, and between the nut and the BeO washer. An attempt was made to improve thermal conduction through the lower path by applying a film of Apiezon vacuum grease along the threads and putting indium between the nut and the BeO washer; however this made no appreciable change in overall thermal resistance.

Several power transistor manufacturers have attempted to combine the necessary thermal conduction and electrical insulation by insulating the collector from the transistor case internally, as in the 2N1724/I (identical to the 2N1724 except for this modification); this transistor therefore may be mounted directly on the heat sink. A test run in vacuum showed that direct contact between the two metal surfaces still gave a high thermal resistance, 5.16 °C/watt; this could be lowered considerably by the addition of indium foil to the interface. However measurements made with the 2N1724/I transistor showed it to have a thermal resistance from collector junction to case of 1.17 °C/watt, while that of the 2N1724 transistor was 0.36 °C/watt. If the latter transistor is provided with the indium-BeO washer method, the total resistance from junction to the heat sink is 0.98 °C/watt, which is less than the junction-to-case resistance alone of the modified 2N1724/I transistor.

CONCLUSIONS

In summarizing, several facts stand out as important in the problem of cooling a power transistor in a space environment by conduction to a heat sink. The use of a soft interface foil is highly effective. Indium foil, used as an interface material, reduces interface resistance to almost 1/8 of its normal value; and the ease with which it may be shaped to the required geometry makes it very desirable. The use of aluminum and copper foils, which offer some reduction in interface resistance, depends on the amount of thermal conductivity desired.

The effect of surface pressure, although critical when no interface material is used, is not of too much importance when indium foil is employed. At very high pressures the effect probably could be made appreciable; however cracking of the BeO washers prevents this. It might be noted that the use of indium along the faces of the washers allows a sizeable increase in the amount of torque that may be applied to the transistor nut before the washers crack.

The process of soldering the transistor to the BeO washer and the washer to the heat sink provided effective cooling. The indium eutectic solder used between the case and washer proved very satisfactory, not only because of its conductive properties but also because of its low melting point, which decreases the danger of harming the transistor during soldering.

RECOMMENDATIONS

As a result of this investigation, recommendations can be made concerning the most efficient methods of cooling a power transistor in a vacuum. First, the insertion of indium foil at the interface between the BeO washer and the heat sink and between the BeO washer and the transistor base is sufficient to reduce the thermal resistance between case and heat sink to a very low level. Thus the indium foil aids in maintaining the junction temperature within its maximum permissible value while the transistor is able to dissipate a fairly large amount of power. The use of indium in space will necessarily depend on its rate of sublimation and consequent deterioration. Reference 8, however, indicates that, even at a temperature of 400 °C, the rate of sublimation of indium in space is only 10^{-5} centimeters per year, which is less than that of lead or zinc. Since the temperature encountered by the indium in this application is less than 100 °C, it is felt that sublimation will be no problem.

A second recommended procedure for cooling in a vacuum is to metallize the BeO washer and to solder the transistor to washer and the washer to the case. This method provided roughly the same thermal resistance from case to heat sink as the previous method involving indium foil.

The first procedure recommended, the indium foil, appears more advantageous because of its ease in assembly and adaptability. Once the joints have been soldered, it would be impossible to remove the transistor from the heat sink easily. Further, it is felt that the former method gives a more reliable joint, which would better tolerate vibration and shock.

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Appendix A

Measurement of the Junction Temperatures

The transistor junction temperature T_j can be determined by measuring electrical parameters of the transistors that are functions of T_j. The parameter used in this experiment was the forward voltage drop V_{CBO} from collector to base with emitter open. A schematic of the circuit used to make this measurement is included as Figure A-1 (also, see Reference 9).

To determine the relation between V_{CBO} and T_j for each transistor, the transistor — in a nonoperating condition — was placed in an oven and heated to temperatures in the transistor's operating region (between room temperature and 100°C). At each temperature the transistor was allowed to reach a constant temperature throughout its structure. The switch (S-1 of Figure A-1) was then closed, so that the relay D-1 energized momentarily at set intervals and permitted V_{CBO} to be measured on the oscilloscope and the calibration curve to be plotted (Figure A-2).

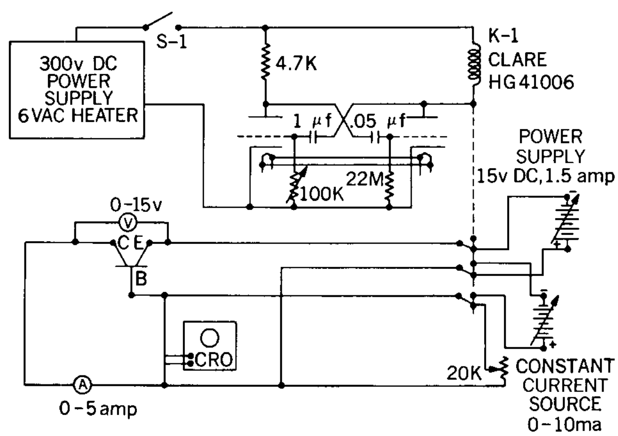

Figure A-1—Circuit for measuring heat dissipation and V_{CBO} of a transistor.

In the actual tests the transistor first was mounted on a metallic plate serving as a heat sink and then was placed in a bell jar, which was evacuated to a vacuum of 10^{-5} mm Hg (Figure A-3). Electrical connection was provided between the transistor and the circuit of Figure 3. Power into the transistor was varied by means of the rheostat in the base lead of the transistor; the emitter-to-collector voltage V_{EC} was kept constant at 14 volts while the emitter current I_E was varied. At each power level, the transistor temperature was allowed to stabilize, with the assumption that the input power would be equal to the heat dissipated per unit time. For each configuration three or four different power levels were used. Switch S-1 was then closed, activating the multivibrator; subsequently power was switched from the power circuit to the V_{CBO} measuring circuit and back. The transistor remained in an operating condition for intervals of 2.25 seconds and was in the measuring circuit for 100 milliseconds. Since the switching time was in the order of 2 milliseconds, it was possible to read V_{CBO} before the junction temperature had decreased from its operating value. The value V_{CBO} was then measured, converted to degrees centigrade, and recorded.

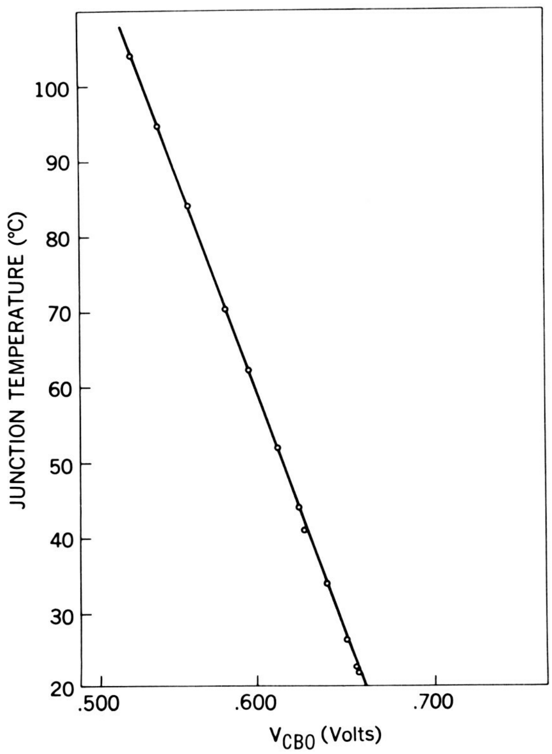

Figure A-2—Junction temperature vs. V_{CBO}, 2N1724 transistor.

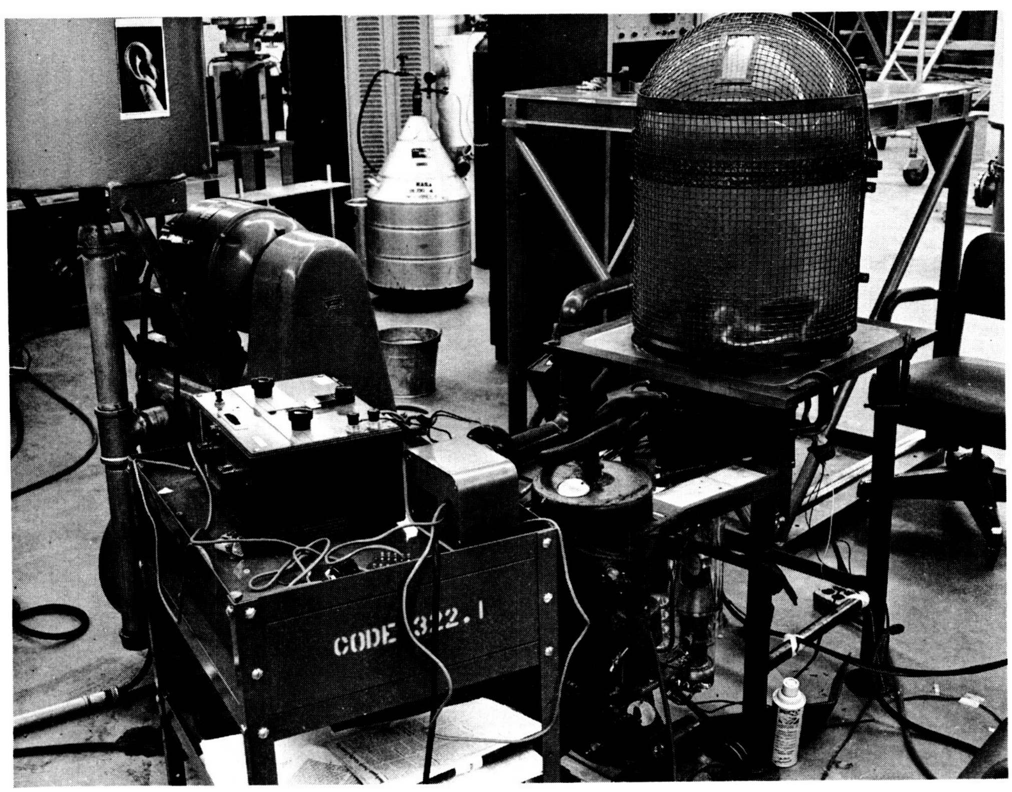

Figure A-3—Experimental equipment.

NASA-Langley, 1963 G-352